Swarm Flyby Gravimetry

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1 Executive Summary

This study describes a new technology for discerning the gravity fields and mass distribution of a solar system small body, without requiring dedicated orbiters or landers. Instead of a lander, a spacecraft releases a collection of small, simple probes during a flyby past an asteroid or comet. By tracking those probes from the host spacecraft, one can estimate the asteroid's gravity field and infer its underlying composition and structure. This approach offers a diverse measurement set, equivalent to planning and executing many independent and unique flyby encounters of a single spacecraft. This report assesses a feasible hardware implementation, derives the underlying models, and analyzes the performance of this concept via simulation.

In terms of hardware, a small, low mass, low cost implementation is presented, which consists of a dispenser and probes. The dispenser constains roughly 12 probes in a tube and has a total size commensurate with a 6U P-Pod. The probes are housed in disc shaped sabots. When commanded, the dispenser ejects the top-most probe using a linear motor. The ejected probe separates from its sabots and unfolds using internal springs. There are two types of probes, each designed for a particular tracking modality. The reflective probe type, tracked by a telescope, unfolds to form a diffusely reflective sphere. The retroreflector probe type, tracked by a lidar, unfolds to form a corner-cube retroreflector assembly. Both types are designed to spherical so that their attitude doesn't affect the spacecraft's tracking performance.

This analysis indicates that the point-mass term of small bodies larger than roughly 500 m in diameter can be observed from a host spacecraft that tracks locally deployed probes throughout a flyby to an uncertainty of better than 5%. The conditions by which this measurement is possible depends on the characteristics of the asteroid (size, type), the flyby velocity, and the type of tracking available (angles-only or angles+ranging). For most encounters, a few (1-3) well placed probes can be very effective, with marginal improvement for additional probes. Given realistic deployment errors, an encounter may require roughly 10-12 probes to ensure that 1-3 achieve their target. Long duration tracking of probes flying by large asteroids (>5 km diameter) can sometimes provide observability of the gravity field's first spherical harmonic, J_2. In summary, this method offers a feasible, affordable approach to enabling or augmenting flyby science.

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2 Introduction

Asteroid gravimetry has important relevance to space-science, planetary defense, and future human spaceflight. Gravimetry gives insight into an asteroid or comet's internal composition and structure, which cannot be studied by imagers, spectrometers, or even surface samplers. It has implications for the formation models of our solar system, since many small bodies are thought to be remnants of the solar system's early states. Consolmagno, Britt, and Macke[1] suggest that just knowing an asteroid's or comet's density and porosity can give important insights into the early solar system's accretional and collisional environment. Asteroid gravimetry also has implications for human spaceflight since near-Earth objects are considered as targets for human exploration. There is a need to characterize our near-Earth neighborhood in order to select candidate targets and assess their expected material properties. There is value in being able to confidently predict how different handling, anchoring, or landing approaches will operate on a particular class of target. Likewise, small body compositional and structural knowledge is required for many proposed missions to mitigate asteroid impacts at Earth. For example, an asteroid's response to an impactor will depend principally on its interior composition and mechanical properties. Asteroid interior data may suggest that certain classes of asteroids would be more safely diverted using other concepts, such as gravitational tugs. Asteroid composition models will improve the fidelity of asteroid-Earth impact predictions and thus provide a more complete understanding of the risks posed by different asteroids.

A body's gravity is typically observed by measuring its effect on the trajectory of a smaller neighbor, such as a moon or spacecraft[2]. That is, by tracking the moon or spacecraft's motion, one can estimate properties of the object's gravitational field. If the gravitational effects are observable, then the quality of the estimate depends on the number, geometric diversity, and accuracy of the tracking measurements. For small bodies, these measurements are difficult to attain. Few asteroids have companions that can be tracked, so we have to rely on observations of spacecraft for high accuracy results. This is achieved by maneuvering a spacecraft to fly past, orbit, or land on a small body while tracking the spacecraft from the ground. While orbiters and landers offer the highest quality science, they require dedicated missions and are often constrained to a single target due to practical Δv limitations.

Flybys are favorable because they are often easily added to existing mission designs with little impact to cost or operations[3,4]; however, they present many challenges for gravimetry. Flybys are typically short-lived events owing to relative velocities of many km/s. The magnitude of deflection from an asteroid is a function of the mass of the asteroid, the asteroid-spacecraft relative velocity, and close-approach range to the center-of-mass. For typical relative velocities (5-15 km/s) the spacecraft must pass very close to the asteroid to achieve a measurable deflection. The high relative velocity implies a short-time-duration conjunction and the asteroid exerts only a weak gravitational force that diminishes in proportion to r^{-2}. The close proximity represents a risk, or operations challenge, to the mission. In addition, low-altitude passes may degrade the science from other instruments that cannot accommodate the high spacecraft slew rates required to track the object during a close pass (e.g., cameras or spectrometers).

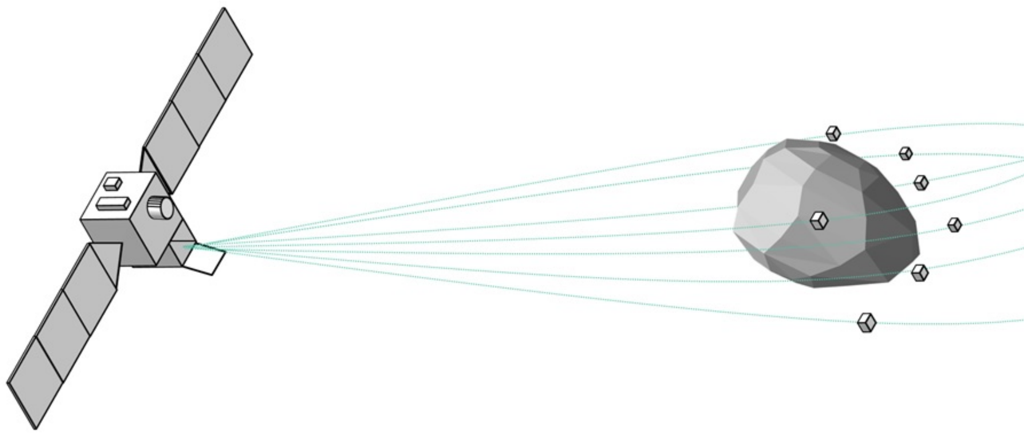

Figure 1: Spacecraft flyby of an asteroid with the spacecraft tracking its ejected probes.

This paper describes a method to enable or augment gravimetry during flybys of small-bodies without imposing a low-altitude spacecraft flyby. Instead, the spacecraft acts a host to a group of small deployable probes[5,6], as shown in Figure 1. The host spacecraft releases the probes just prior to a flyby. The probes diverge from the host and pass the small body from a variety of ranges and directions. Each probe's motion represents an independent flyby. The host spacecraft tracks each probe's pre- and post-encounter relative positions and downlinks this data to the ground. Once the measurements are received, an estimation technique is used to solve for the best-fit orbit parameters and the small body's mass. Given a large quantity of probes and a rich diversity of probe trajectories, this solution can have sufficient fidelity to yield a gravity model. Combining this model with a surface profile derived from optical or altimeter measurements may give insight into the asteroid's mass distribution and composition.

This approach is similar to that studied by Grosch and Paetznick[7] and Psiaki[8] who used a set of relative measurements over a series of orbits to estimate the inertial position of deployed probes and the central body's gravitational terms. Likewise, Muller and Kachmar[9] analyzed the use of relative measurements of deployed probes to estimate inertial terms in a host spacecraft's dynamics.

The probes need only be trackable, which implies that they may be very simple, low-cost, and easily accommodated on-board a spacecraft. If properly deployed, they can yield many measurements among many independent paths, which improves the observability of the gravimetry problem. In addition, most measurement types benefit from short ranges, offering higher signal-to-noise measurements relative to the host spacecraft than could be achieved relative to an Earth based ground station. Finally, the probes can conceivably be deployed to pass within a very short range of the small body's surface, which allows the host spacecraft to maintain a safe distance that is optimal for other instruments. The probes' reduced magnitude of closest approach will yield a corresponding increase of their trajectory change when compared to that of the spacecraft. For a nominally spherical asteroid of fixed mass, the efficacy of this technique is limited by the asteroid's *density*. Higher density asteroids will permit the probes to reduce their distance of closest approach (relative to the center-of-mass), thus increasing the asteroid's perturbation of the probes from their nominal trajectories and improving the accuracy of the estimation results.

This report describes a set of candidate system architectures, including a variety of tracking methods and a candidate deployment technique, which are analyzed via simulation. The analysis includes a definition of the state vector, the dynamics model of the flyby, several different measurement models, an appropriate estimation algorithm, and a covariance simulation. The simulation and estimation approach are evaluated over a trade-space that assesses relevant parameters.

3 System Architecture

The system is composed of three principal components: the tracking method, the probe design, and the deployment method. A successful architecture addresses each of these components in a manner that results in high-quality gravimetry while imposing as few constraints or burdens on the host spacecraft or mission. The tracking method and probe design are tightly coupled and are presented together, while the deployment method is considered separately.

3.1 Tracking Method and Probe Design

The host spacecraft must detect and track each probe throughout the flyby. For large numbers of probes, the tracking method should ideally facilitate differentiation among the probes and measurement attribution. Alternatively, one could pursue multiple hypothesis models that would consider each measurement's association with each probe. Table 1 lists six candidate tracking methods. In addition to the parameters listed, the options also differ with respect to the required burdens to the host spacecraft and required complexity of the probe design. Each of these approaches is described in greater detail below.

Table 1: Candidate Tracking Methods

Sensing Type	**Power Source**	**Measurement Type**	**Differentiation**
Optical	Sunlight Reflection (Sun)	Angles	Challenging
	LED Illuminators (Battery)	Angles	Possible
	Laser Irradiation (Host Spacecraft)	Angles and Range	Built-In
Infrared	Powered Heaters (Battery)	Angles	Possible
Radio	RF Beacon (Solar, Battery)	Doppler and/or Range	Built-In
	Radar Reflection (Host Spacecraft)	Doppler and/or Range	Possible

1. **Sunlight Reflection** - One favorable candidate method requires that the probes be reflective to sunlight. The host-spacecraft then uses its on-board imager to detect and track the probes as they drift away from the spacecraft and flyby the small body. This approach requires a low solar phase angle (the angle connecting the sun-probe-imager points) so that the probes' reflections are visible to the spacecraft. This can be achieved by deploying the probes in the anti-sun direction. The reflection is dependent on the probe's shape, size, and reflectivity properties.

2. **LED Illuminators** - In this method, light-emitting-diodes (LED) are tracked by their optical signature. These can operate independently of the sun-relative geometry. The probes would consist of batteries and flashing LEDs. Here, the probes' detectability depends on the number and brightness of LEDs. This is reminiscent of the Japanese FITSAT-1 cubesat[10], which was

observable at ranges of 100's of kilometers using standard telescopes with long integration times.

3. **Lidar** - Ranging lasers were used on the Gravity Recovery and Climate Experiment[11] (GRACE) and Gravity and Interior Laboratory[12] (GRAIL) missions. This implementation offers the highest quality measurements, but imposes requirements on the host spacecraft, which must accommodate and point a laser. In this instantiation, the probes could consist of assemblies of corner-cube retroreflectors[13,14], which would give very high returns at nearly any attitude. This would help to mitigate the losses associated with range (d^{-4}). It may be possible to use an existing laser altimeter designed for surface science.

4. **Powered Heaters** - If the host spacecraft carries a focal plane sensitive to infrared wavelengths, it may be possible to detect heated probes' thermal signatures. The performance and duration of the probes are limited by the available on-board power storage. For practical battery sizes, the effective tracking range is relatively short. In addition, the tracking accuracy is likely low given the poorer relative quality of available infrared focal plane arrays.

5. **Radio Frequency (RF) Beacons** - If each probe is equipped with a radio-frequency beacon, it could be readily identifiable with an on-board radio subsystem. Differentiation would be straightforward via time-division, channel-division, or code-division multiple access approaches. One likely challenge is the measurement quality associated with an on-board oscillator. The change in relative velocity is quite small between the probes and the host-spacecraft. This requires a very stable probe oscillator during the whole encounter. Otherwise, thermal variation in the oscillator could overpower any induced frequency variation.

6. **Radar Reflectors** - If each probe is reflective in an RF sense, it may be possible to detect and track very simple probes over long ranges using a radar instrument on the host spacecraft. Here, the signature is defined by the probe's radar cross section. One probe implementation could consist of simple metal dipoles[15], as is used in radar chaff or was used in Project West Ford[16]. A higher return design would use corner cube retroreflector[13] assemblies[14]. The longer wavelength of the radar signal eases the probe's reflection and flatness tolerances, which facilitates production. This approach burdens the host spacecraft with carrying a dedicated radar payload, of which many space-qualified designs currently exist.

Two feasible deployable probe concepts were designed. The first probe design addresses the sunlight-reflection case and constitutes of an expanding, 10 cm diffuse sphere. The exterior is a white fabric wrapping a thin spring-metal frame. When compact, the probe fits in between two sabots, which house it prior to ejection. This is illustrated in Figure 2.

The second probe design applies to the lidar and radar tracking methods. This design consists of a central mirrored disc, with 8 unfolding mirrored sides. The compacted shape is a thin disc that fits within two sabots. Once the sabots are removed, the probe's sides unfolded (via torsion springs), and the assembly consists of 8 corner-cube retroreflectors as illustrated in Figure 2.

Both probe designs are spherical, such that they give a high signal-to-noise return in any orientation. Additionally, this facilitates the characterization, calibration, and estimation of solar radiation pressure, which is treated as an error source in this analysis.

3.2 Deployment

The host spacecraft must release each probe onto a trajectory that passes within a short range of the target body along an independent, diverse path without subsequently interfering with the host spacecraft. Given the very low values of imparted Δv by the low-mass small-bodies, the probability of a probe recontacting the spacecraft is insignificant.

A favorable deployment architecture consists of a combination of spacecraft pointing, spacecraft thrusting, and a hardware deployment mechanism. Multi-payload deployment has been demonstrated with cubesats, which are routinely deployed from launch vehicle upper stages without interfering with the primary mission payloads. Here, the vehicle points the cubesat's compressed-spring deployer along a desired direction, releases a stop that allows a spring to extend and impart a relative separation velocity to the cubesat, and then executes a small collision avoidance maneuver to prevent any future recontacts. This process would be useful for the flyby application as well, in that the deployment benefits from the spacecraft's high-quality attitude control and timing, to place the probe on a low-altitude pass of the small body. Compression springs introduce a non-negligible level of uncertainty to the deployment. As an alternative, a small controllable solenoid could be commanded to eject each probe. An accurate deployment process would include extensive pre-launch component characterization, and it would include a study of performance degradation due to the long storage times between assembly, launch, and use.

A dispenser has been designed to accommodate the two types of probes. The dispenser consists of a tube that contains roughly 12 probe assemblies. The probes are contained within low-friction disc sabots. When commanded, the top-most probe assembly is ejected using a linear motor. The motor pushes the probe assembly completely out of the "chamber" and then returns to a rest-state. The next probe assembly is then pushed into place for ejection by a compression spring. The size (35 cm x 25 cm x 15 cm) and mass (< 8 kg) of the dispenser is meant to be commensurate with a 6U P-Pod CubeSat deployer. The linear motor requires 20-200 W of power at the time of ejection. The housing and sabots were rapid-prototyped, as shown in Figure 3.

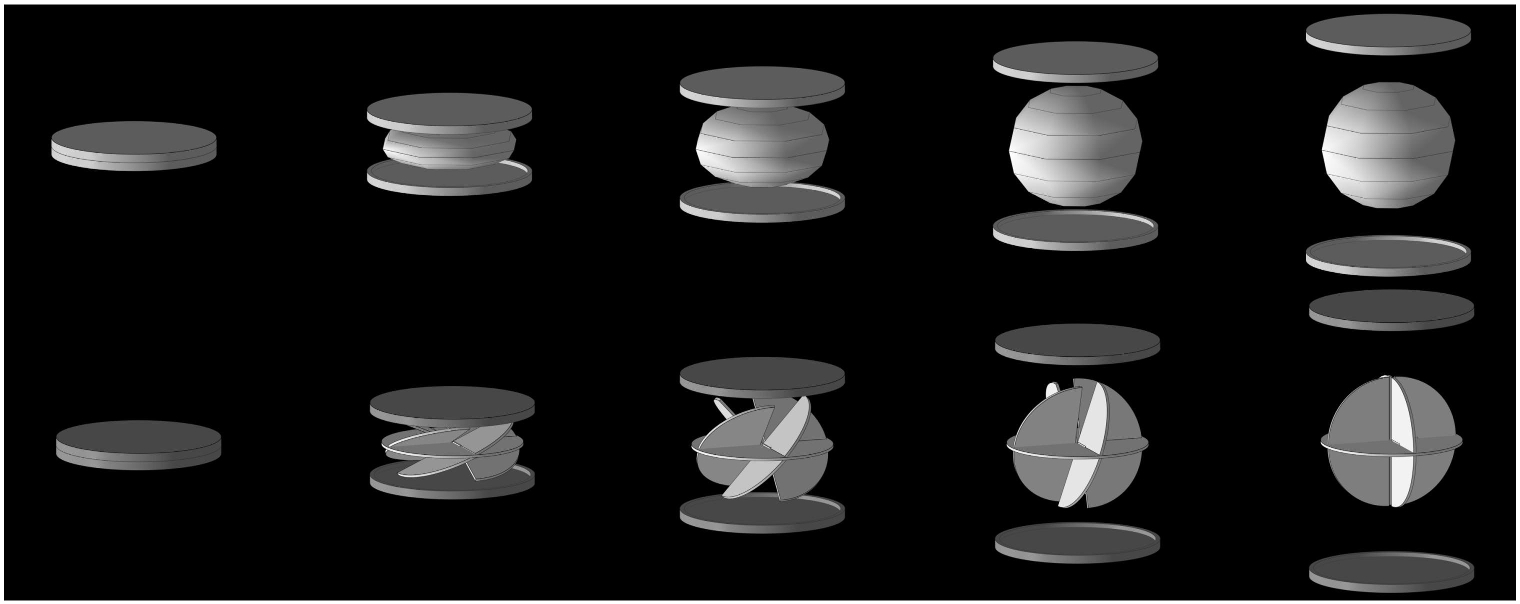

Figure 2: Conceptual designs for dispensed optically reflective probe (top) and corner-cube retroreflector probe (bottom).

Figure 3: Photograph of dispenser concept prototype.

4 Analysis

4.1 System State Definition

The following analysis is based on models of the probes, host spacecraft, and the asteroid. The parameters that define these models are referred to as the states of the system. These states can be combined to form one system state vector with the following definition:

$$X = \left[\ \underline{r}_1 \ , \ \underline{r}_2 \ , \ \ldots \ , \ \underline{r}_N \ \middle| \ \underline{\dot{r}}_1 \ , \ \underline{\dot{r}}_2 \ , \ \ldots \ , \ \underline{\dot{r}}_N \ \middle| \ g_1 \ , \ g_2 \ , \ \ldots \ , \ g_M \ \right]^T \tag{1}$$

where $\underline{r}_i$ is the 3-by-1 position vector of probe i for $i = 1\text{–}N$, $\underline{\dot{r}}_i$ is the 3-by-1 velocity vector of probe i, g_j is the j^{th} coefficient of a yet-to-be-defined parameterization of the asteroid gravitational field for $j = 1\text{–}M$, and $*^T$ i s the transpose of the quantity $*$. The terms $\underline{r}_i$ and $\underline{\dot{r}}_i$ are defined as:

$$\underline{r}_i = [x_i \ \ y_i \ \ z_i]^T \tag{2}$$

$$\underline{\dot{r}}_i = [\dot{x}_i \ \ \dot{y}_i \ \ \dot{z}_i]^T \tag{3}$$

The selection of the reference frame and the gravity model are deferred until the next subsection.

The following analysis is based on two different types of state-space models[17]: a dynamics model and a measurement model. The dynamics model describes the way that all of the states change over time, and the measurement model defines the functional dependence of the measurements on those same states.

4.2 System Dynamics

The dynamics of the probes are modeled as obeying the following equation:

$$\underline{\ddot{r}} = f\left(\underline{r}\right) + \underline{d} \tag{4}$$

where $\underline{\ddot{r}}$ is the second time derivative of the position vector $\underline{r}$, $f\left(\underline{r}\right)$ is the position dependent gravitational acceleration, and $\underline{d}$ is the acceleration term associated with all other perturbations, including solar gravity, n-body gravity, and solar radiation pressure.

The secondary accelerations modeled by $\underline{d}$, while non-negligible, are treated as constant over the period of the flyby encounter among all the probes. This assumes that the value of these terms is insensitive to variation in each probe's local position over the encounter. In the case of solar radiation pressure, this assumes that a campaign was conducted to characterize the optical parameters for each probe prior to launch. Alternatively, the probes can be designed such that the solar radiation pressure acting on each probe is attitude-independent and consistent among all of the probes.

This work uses the center of mass of the asteroid as the center of its coordinate system. For this analysis, g_j consists of the first M coefficients in a spherical harmonic expansion.

The system state vector's nonlinear time derivative is:

$$\dot{X} = \left[\ \dot{\underline{r}}_1\ ,\ \dot{\underline{r}}_2\ ,\ \ldots\ ,\ \dot{\underline{r}}_N\ \middle|\ f\left(\underline{r}_1\right)\ ,\ f\left(\underline{r}_2\right)\ ,\ \ldots\ ,\ f\left(\underline{r}_N\right) \middle|\ \ 0_{1\times M}\ \right]^T \tag{5}$$

where the bottom subvector indicates that the gravitational parameters are constant throughout the simulation. $f\left(\underline{r}_i\right)$ is a 3-by-1 vector that represents the computation of the small body's nonlinear position-dependent gravitational acceleration for the i^{th} probe.

5 References

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